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HIGH-SPEED INTERNET ACCESS

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Explanatory Notes

E=m·c²	Definition
	Interesting
i	Note
	Example
	Summary
+	Advantage
–	Disadvantage

ANNOTATION

VDSL2 and G.fast connections are designed to deliver new services via symmetrical copper pairs and fiber optic in access telecommunications networks. VDSL2 connections follow the older ADSL technology and bring to subscriber higher transmission speeds. In addition, symmetry and optimization of transmission speeds for upstream and downstream are allowed. Nowadays VDSL2 connections and G.fast are latest evolutionary steps in xDSL technologies and their implementation to access telecommunications networks are also part in the concepts of FTTx networks.

OBJECTIVES

The material introduces the principle of VDSL2 connections and G.fast, possible variations, used modulation and coding. The achievable transmission rates and the possibilities of connection of the new generation of xDSL are presented. The basic knowledge of the properties of telecommunication lines and basic methods of digital transmission and signal processing in studying this module are expected.

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1 Telecommunication networks and digital subscriber lines

1.1 Communications and telecommunications

Telecommunications is a discipline concerned with their communication man (transmission of messages) in conditions that are not able to overcome their natural senses. Telecommunications therefore falls within the field of science communication equipment and also communications technology and modern development basically began in the nineteenth century, the invention of the telegraph and later telephone. Today is an integral part of the field of **ICT** (*Information and Communication Technology*).

Word “telecommunications” was created by combining of two words. The Greek word “tele” (means remote) and the word “communication” (means information exchange).

Devices for communication at a distance are known as telecommunication equipments. Telecommunication network is subsequently formed by interconnected telecommunication devices and nodes.

It is obvious that it is not possible to interconnect direct links all telecommunications devices, or all participants of communication. For this reason, the telecommunications network to be logically structured in a certain way so that it can meet the requirements of a large number of end users in different geographical areas. The telecommunications network is divided into two parts. On the part of the backbone and access.

If we wanted to create a telecommunication network so that we mutually supportive all the participants among themselves, it would mean if just 10 subscribers to realize a total of 45 lines.

1.2 Telecommunication network

It has already been mentioned that the telecommunications network must be structured in a certain way. Usually divided into two main parts – core (backbone) and access. Both have their challenges and characteristics.

The core telecommunications network aims to interconnect various network nodes of telecommunications provider. All data transactions are concentrated in these nodes from all subscribers and after that it can be effectively transferred through the shared telecommunications paths through wide geographic area. Typical for this network is:

- standardized transmission medium is single-mode optical fiber,
- transmission speed range in the tens Gbit/s,
- operational distances are from tens to thousands kilometers,
- ring topology is a typical network topology.

Access telecommunication networks mean part of the telecommunications network, which is the last point between provider and subscriber. Over the last point, the **ISP** (*Internet Service Provider*) is usually considered local exchange HOST or **RSU** (*Remote Subscriber Unit*). Harness coming from the main distribution switchboard (or from **RSU**) in the network and street cabinets gradually branches into different directions to end subscribers. Typical for this network is:

- transmitting medium is symmetrical metallic pair (single-mode optical fibers are optional),
- transmission speed range from ones up to hundreds Mbit/s,
- operational distance is hundreds meters to ones kilometers,
- commonly occurring network topology is a tree topology.

1.3 Metallic access network

The access telecommunications network are based on symmetrical copper pairs in most European countries. Conception design of the network counted mainly with the provision of telephone services via analogue phone lines **POTS** (*Plain Old Telephone Service*) in the frequency range from 300 Hz to 3400 Hz (ie. classical telephone channel) or basic digital connections **BRA-ISDN** (*Basic Rate Access - Integrated Services Digital Network*) in the range up to 80 kHz.

The access networks of largest telecommunications providers in the Czech Republic are based on metallic cables whose basic element is a spiral quad and symmetrical pair.

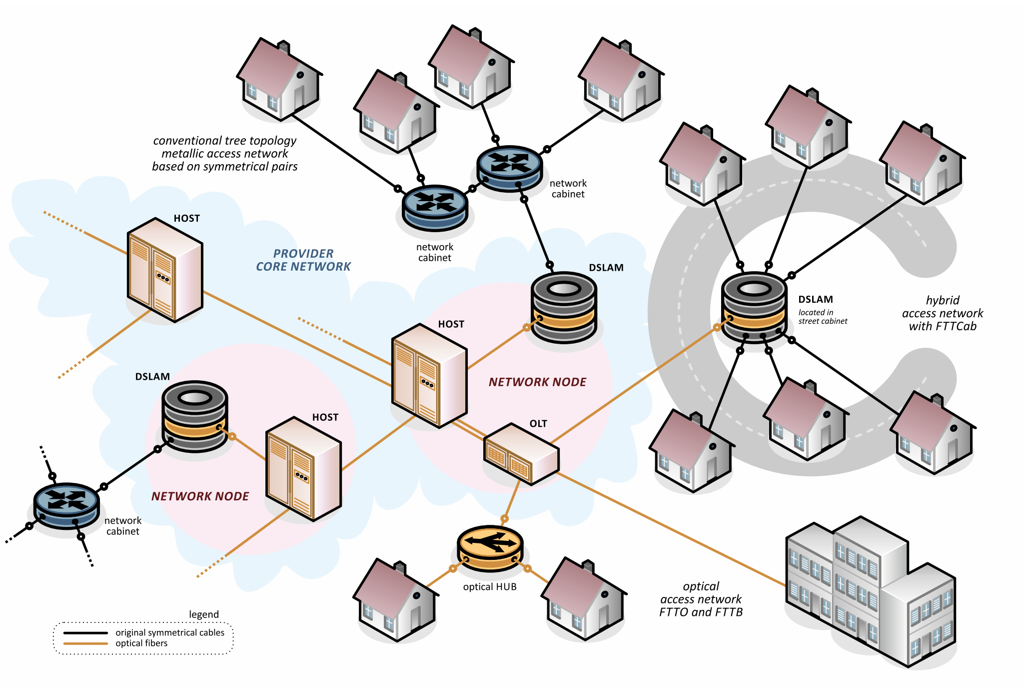
Cables using wires with copper cores with diameters of 0.4, 0.6 and 0.8 mm diameter insulation max. 1.7 mm and have an outer casing predominantly of polyethylene. Cables in the bearing are filled with a suitable embodiment the filling material (gel), which forms protection against water. Conductors have polyethylene foam isolation. Cables in the self-supporting version (hanging cables) are not filled and full use polyethylene isolation. Part of the access network in the Czech Republic but also uses historical copper cables with copper conductors with diameters of 0.4, 0.6 and 0.8 mm with an air-paper isolation.

Access networks other telecommunications operators are, in comparison to the largest network providers, relatively small and covering a small geographic area. For this reason, throughout this module we discuss parameters and operating conditions of the network elements in the access network only the largest providers.

1.4 Hybrid access network

Nowadays it is necessary to provide to subscribers new services than just phone service. Above all, it is a high-speed data transfer and access to the global Internet network, the transmission of television and video signals. Possibilities of metallic access network but nowadays approaching their limits. Physical parameters of twisted pair (attenuation, group velocity of propagation, crosstalks, etc.) significantly reduce transmission parameters such as transfer rate and prevent its further increase. The solution to this situation is to replace the symmetrical pairs in the access network for optical fibers. Given the conventional topology of the access network, however, this solution is too expensive. Therefore, the replacement of copper pairs for optical fibers takes place gradually since the **ISP** network node towards the end subscriber. Such access network abbreviated **FTTx** (*Fiber to the x*), where character x is a wildcard, which indicates the point of termination of the optical fiber. The main types of **FTTx** networks are:

- **FTTH** – *Fiber To The Home*
- **FTTO** – *Fiber To The Office* (means to the office or business premises)
- **FTTB** – *Fiber To The Building*
- **FTTC**, **FTTCab** – *Fiber To The Curb*, *Fiber To The Cabinet* (means to a local cabinet or sidewalk column) with a length of copper wire up to 300 m,
- **FTTN** – *Fiber To The Node* (to a local hotspot - street cabinet, column) with a length of copper wire over 300 m,
- **FTTEx** – *Fiber To The Exchange* (means to the local digital exchanges),
- **FTTdb** – *Fiber To The Distribution Point.*



Example of classical metallic access network, hybrid access network based on concept FTTCab and fully optical access network

1.5 Digital Subscriber Lines

Terminal equipments of **xDSL** (*Digital Subscriber Line*) are specially designed to allow better use of the potential of copper in the access network infrastructure. A common feature of these systems is relatively high transmission speed in the order up to tens of Mbit/s. Digital subscriber lines can be classified according to various criteria. One major division is according to a method of transmission to digital transmission connections in:

- baseband (**HDSL** (*High-speed Digital Subscriber Line*), **SHDSL** (*Symmetrical High-speed Digital Subscriber Line*)),
- modulated band (**ADSL2+** (*Asymmetrical Digital Subscriber Line*), **VDSL2** (*Very high-speed Digital Subscriber Line*) and G.fast) and it can be operated on subscriber lines together with already installed another service operated on the baseband, for example **POTS** or **ISDN-BRA**.

In the case of purely metallic solutions of the access network, where the connection to the provider terminating near the main distribution exchanges, can use *ADSL*, **SHDSL** and on limited distance also second improved generation **ADSL2+** and **VDSL**. In the case of hybrid optical and metallic access network solutions, where there are facilities at the provider of extended closer to the subscribers can take full advantage of connections **ADSL2+** and **VDSL2** and G.fast.

2 Digital subscriber line VDSL2

2.1 Basic features of VDSL2 connection

Digital subscriber line **VDSL2** is a second generation of **VDSL** connection. However, significant and proven innovation is not surprisingly taken from its original specification of **VDSL**, but it is taken from the second-generation connection **ADSL2**. This is particularly the grid encoding (known as Trellis Code) for the ability to repair the receiver single bit errors and the ability to correct error bursts caused by the impulse interference using a Reed-Solomon code and data interleaving. Like **ADSL2** transmission speed can be changed during operation **SRA** (*Seamless Rate Adaptation*), controlling the transmission power to reduce crosstalks to neighboring pairs, and activate power saving mode (known as Sleep Mode).

E=m·c²

The basic recommendation which standardizes the connection of the **VDSL2** is ITU-T G.993.2.

Increasing the transmission rate to obtain an extension utilized frequency band up to 30 MHz. For comparison, **ADSL2+** connection uses a frequency band only up to 2,208 MHz. Maximum transmission speeds ranging from tens to hundreds of Mbit/s. In the downstream direction, the maximum value of around 200 Mbit/s.

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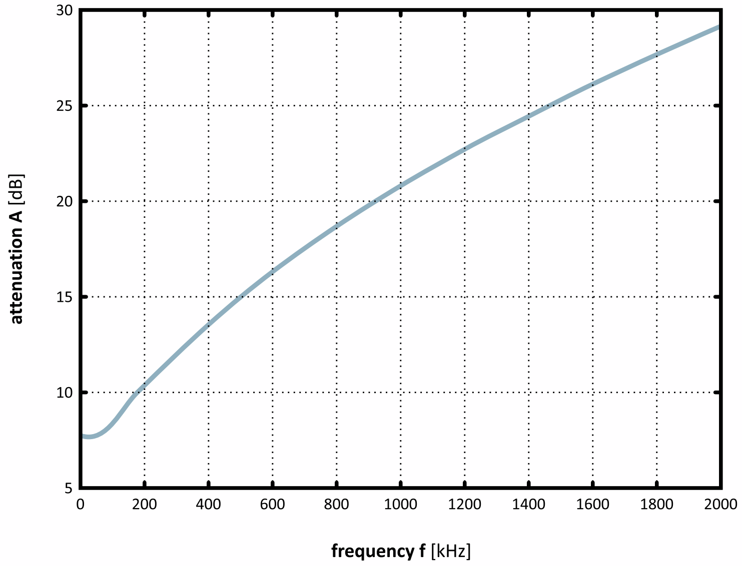
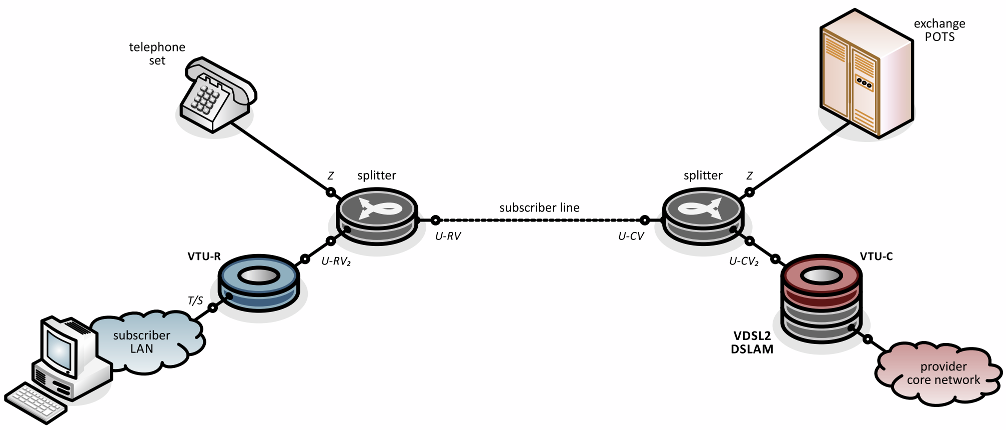
However, extending of utilized frequency band has one big disadvantage. The maximum length of the local loop, which can be operated on **VDSL2** connection, is shorten in comparison with **ADSL2+** connection. The attenuation of line in specified frequency band is growing with increasing frequency bandwidth.



The next figure shows the attenuation course of the twisted pair depending on the frequency (cable length 1 km, average live wires 0.4 mm, copper material). Symmetrical pair is located in a classic local quad cable in construction TCEPKPFLE.

2.2 Layout of VDSL2 connection

As it is already mentioned, **xDSL** connections allow more efficient utilization of existing local loops (based on metallic symmetrical pair) for the provision of new services than those for which it was the lines originally designed. Therefore, it must be assumed that the service **POTS** or **ISDN-BRA** is already on the lines operated together with a **VDSL2** connection and it must not in any way affect this coexisting service (this applies, of course, vice versa). For this reason, **VDSL2** connection operates in the modulated frequency band and both services on the subscriber line is additionally separated by frequency filters called as Splitters. Telephone and data signals can be transmitted in both directions over the same line in the same time.



The basic diagram of the **VDSL2** connection is similar to the older **ADSL** connection.

High-speed transmission of digital signals at **VDSL2** connection provide the modems **VTU-R** (*VDSL2 Termination Unit - Remote*) on the subscriber side and **VTU-C** (*VDSL2 Termination Unit - Central*) on the provider side. The modem at the side of your provider is usually part of the local multiplexer called as **DSLAM** (*DSL Access Multiplexer*), which centralizes the digital streams from all connections in the specified locality.

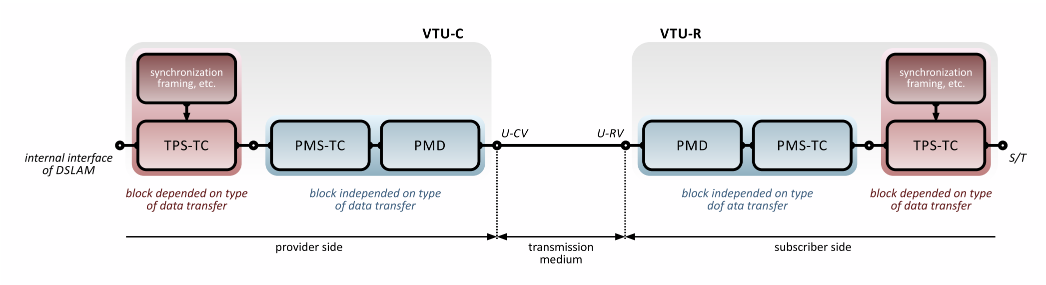
The basic diagram includes the following functional blocks and interfaces:

- **DSLAM - DSL** subscriber multiplexer,
- Splitter - frequency filter on the subscriber and provider side - in the case of service options without the concurrence of active service **POTS** or **ISDN-BRA** is the splitter optional
- **VTU-C** – **VDSL2** transceiver (modem) on the provider side,
- **VTU-R** – **VDSL2** transceiver (modem) on the subscriber side,
- *U-RV* - physical interface terminating lines on the subscriber side,

- *U-CV* - physical interface terminating lines on the provider side (located in exchange),
- *U-RV2* - physical interface between the splitter and the modem on the subscriber side,
- *U-CV2* - physical interface between the splitter and the modem on the provider side,
- *T/S* - physical interface between the **VTU-R**, followed by the network infrastructure on the subscriber side (**LAN** (*Local Area Network*)),
- *Z/U0* - physical interface twisted pair running **POTS** or **ISDN BRA** with limited frequency band by HUB.

2.3 Layer model of terminal equipment at VDSL2 connections

Functions and features of terminal equipment at VDSL2 connections can be described similarly as for other **xDSL**, through a layer model. The device model includes two basic parts. The first part is independent on the data transmissions, because it contains the functions and blocks that are all end devices associated with the same and adapting the physical data transmission medium. There are blocks of **PMD** (*Physical Media Dependent*) and **PMS-TC** (*Physical Media Specific - Transmission Convergence*). The second part, block **TPS-TC** (*Transport Protocol Specific - Transmission Convergencer*) respects the type of data transfer and the structure of subscriber data and it is depended on the data transmissions.



Layer model of terminal equipment at VDSL2 connections.

The basic function block **PMD** are linked to the actual transmission of signal transmission environment. There are mainly generating and recovery cycle, modulation and demodulation, echo cancellation, compensation of the negative line parameters and initialize the connection.

Block **PMS-TC** is specific depending on the transmission environment and perform functions associated with creating frames, frame synchronization, data security realized by **FEC** (*Forward Error Correction*), interleaving, scrambling and descrambling. There are also in this block the additional subscriber service information added into a bit stream (header of data frames) and implements the service communication between devices.

Parameters of **TPS-TC** block depends on the desired functionality of the terminal device or the type of carried data traffic (type of requested services). Block **TPS-TC** serves as an adaptation block the transport protocol (format of user data), and other lower blocks of **VDSL2** connections. It is responsible for multiplexing, demultiplexing and synchronization of the individual subscriber data that flows according to the required quality of service parameters (flow prioritization of certain services).

Reference points labeled as S/T are interfaces in the direction to user terminals. The description of the parameters of **VDSL2** connections will proceed just a block from the **TPS-TC** towards the block and **PMD** interface U.

2.4 Data transmission modes of subscriber terminal

Parameters of **TPS-TC** block in the layer model of terminal equipment are closest to the participant and meet their functionality requirements depending on the type of data transfer of the subscriber. In current **VDSL2** connections supports block **TPS-TC** three modes of data transfer:

- **STM** (*Synchronous Transfer Mode*). In this mode, all end devices work in the part of access network synchronously depending on the **DSLAM**. Synchronicity means that data transmissions along the upstream and downstream are carried out on all terminals at the same point in the same time.

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The advantage of this transmission mode is the significant reduction of near end crosstalk noise.

- **ATM** (*Asynchronous Transfer Mode*). This method of transmission ensures backward compatibility with existing **ADSL** connections (ie. dual **VTU-R** can work against **ADSL DSLAM**). For data transmission using the cell constant length of 53 bytes, which are transmitted according to the type of content and inserted with the relevant virtual path and channel identifiers **VPI** (*Virtual Path Identifier*) and **VCI** (*Virtual Channel Identifier*).
- **PTM** (*Packet Transfer Mode*) is designed for efficient transmission of streams in which the subscriber data are encapsulated into packets or frames. Typically, this is the Ethernet frame protocol frame Point-to-Point packets or **MPLS** (*MultiProtocol Label Switching*).

$E=m\cdot c^2$

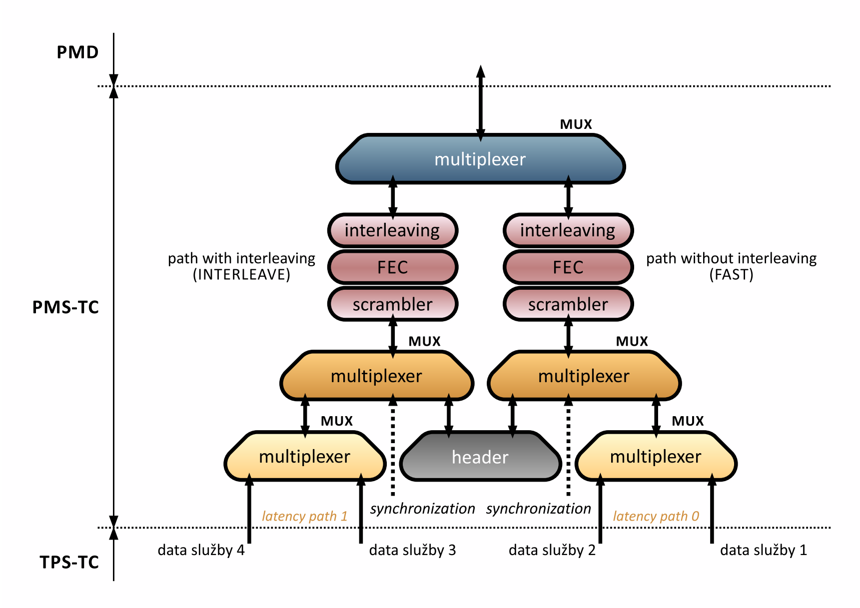
- **PTM** scheme is based on standards known as Ethernet in the First Mile (IEEE 802.3ah), namely solutions for metallic access network based on the 10-TS-PASS.

VDSL2 connection may above the physical layer to support multiple independent data channels includes more services which have a different quality of service requirements. Typically it can be a video transmissions which it is necessary to prioritize traffic in preference with normal data. The data of these services are transmitted via two independent pathways (differentiated by latency path) with independently adjustable parameters such as the depth of interleaving and therefore the delay (dual latency), etc.

Quality of service is a scale how to evaluate the subscriber satisfaction with the service that he pays for, and that it provided by the operator. Evaluation of services is a relatively complicated process. The different criteria are used for the evaluation. For example, starting from a completely objective technical criteria, such as achieving a transmission speed or delay of transferred data, and ending with a completely subjective criteria such as clarity bill or satisfaction with customer support.

2.5 Data transfer capabilities

Block **PMS-TC** is designed to adapt and secure the subscriber data into a format suitable for transmission over twisted pair. It accepts from block **TPS-TC** individual participant data streams. Block **PMS-TC** includes into these data flow headers, formats it into **VDSL2** frames, and ensures randomization of periodic sequences by scrambling, adding a bit of security and interleaving. These procedures are applied to each data flow path separately.



The basic procedure for data processing in the block **PMS-TC**.

Transmission paths for **VDSL2** connections can be in general:

- without data interleaving (mode FAST) - that means, low delay in transmission which is necessary for real-time transmission, but also a low resistance against impulse interference.
- with data interleaving (mode INTERLEAVE) - a higher delay in transmission, which is not a defect, for example, when transferring data to the Internet (typically realized through **FTP** (*File Transfer Protocol*)), but also with higher resistance against impulsive interference.

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Interleaving is a technique that enhances the ability to detect and correct errors resulting from impulse interference during transmission. Corrupted data is possible in the terminal equipment repair and it is not possible to be re-transferred data from the source. This capability leads to increase the transmission efficiency.

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Disadvantage of interleaving is the increasing of transmission delay.

Interleaving gradually created a data frame with subscriber data divides into a number of parts. Ranking individual parts are defined manner swaps (interleaves). This modified frame is sent to the transmission path. Impulse noise during transmission may cause the cluster of errors in the transmitted data frame. On the receiving side, parts of the damaged frames are re-ordered again into the original order. It is very likely that the burst error during re rearrangement into different parts of the framework. Such errors can be stretched to better detect and repair using Reed-Solomon coding (see. Below). The disadvantage is the increase in delay (tens to hundreds of milliseconds) because the data frame to the transmitting side does not transmit immediately after assembly of the lead, but it is necessary to delay it for rearrangement. Similarly, there is a delay on the receiving side. The advantage of striping is to obtain a higher resistance against impulsive noise that bothers especially during video transmissions of encoded **MPEG** (*Moving Picture Experts Group*) standards. For video broadcasts with **MPEG** encoding, the effect of impulse noise manifests itself as so-called "blocking effect". To restore the image information is necessary to wait for the transfer key frame.

2.6 Transfer security

Transmitted data sequence is scrambled in **PMS-TC** block. Scrambling at the transmitting side (and descrambling at the receiving side) is intended to eliminate a periodic sequence of transmitted data stream. Scrambling/descrambling is usually implemented as a shift register with established feedbacks. Scrambling the descrambling operation must be of course completely inverted, so that always occurred to restore the original sequence of data.

Randomization of transmitted sequence of data results brings lower demands on the required frequency bandwidth of the transmission path.

For **VDSL2** connection is made, like in other **xDSL**, security of the data sequence against transmission errors. For the detection of errors is used security using 8-bit word that is generated by calculating a classical cyclic code **CRC** (*Cyclic Redundancy Check*).

FEC is based on Reed-Solomon code **RS**. Error correction in conjunction with interleaving, provides protection against single failures and short burst errors.

When encoding using Reed-Solomon code are formed from solid blocks formed a number of data bytes, and a fixed amount of signaling bytes. The number of security bytes can be an integer ranging from 0 to 16. The full sequence data (including security) can have 32 to 255 bytes. Roughly speaking, the number of bytes that can be used to Reed-Solomon code fix is half than the number of bytes used security.

This method of error correction is very effective for its low redundancy (typically seven percent).

When determining the specific parameters for correction **FEC** and interleaving is a necessary compromise between the degree of error protection and overall transmission delay.

2.7 Variants of VDSL2 connections

Subsequent chapters deal with the parameters of the block **PMD**, through which the terminal is connected to the physical transmission medium - symmetric pair.

VDSL2 connection occurs in several different versions so as to be able to perform tasks at various transmission conditions. The annexes to the basic ITU-T G.993.2 is an international standards organization identified three basic types of **VDSL2** connections. There is specified in recommendation:

- Annex A - **VDSL2** connection to the access network in the North America,
- Annex B - **VDSL2** connection to the access network in the Europe,
- Annex C - **VDSL2** connection to the access network in the Japan.

Common to all three types of connections is a block arrangement of the internal circuits and principles of these circuits. Thus, for example method of securing data flow of subscriber before its transmission in the access network (circuits for synchronization scrambler, convolution encoder, modulator, etc.).

Multicarrier modulation **DMT** (*Discrete Multi-Tone*) is exclusively used for the realization of data transmission for all three types of connections.

The principle of this modulation is used by the division of the entire frequency band into a series of independent subchannels (sometimes also referred to as tones or carriers). Width subchannel may either be the same as the older **ADSL** therefore 4,3125 kHz or 8,625 kHz twice but only for the 30 MHz band. In each sub-sub-channel data of the subscriber are modulated by **QAM** modulation. The number of states of modulation at **VDSL2** connections from 4 up to 32768, which corresponds to 2 or to transfer 15 bits of one modulation state. The modulation rate is 4,3125 kHz subchannel width set at 4 kBd and 8,625 kHz subchannel width is fixed at 8 kBd. Method **FDD** (*Frequency Division Duplex*) can be only used for creation of a bidirectional transmission.

Different profiles, broadcast schedules and frequency masks of **PSD** (*Power Spectral Density*) are set for **VDSL2** connection in various annexes ITU-T G993.2 according to the typical parameters of access telecommunication networks of the specific region.

2.8 Profiles of VDSL2 connections

It was mentioned that increasing of transmission speeds is realized due to an extension of utilized frequency band. But extended bandwidth reduces the maximum length of the local loop, because there is an increase copper transmission path attenuation at higher frequencies. Therefore, with regard to disparities in access networks each region (North America, Europe, Japan), the need to implement data transmission services and various other conditions, connections with **VDSL2** set different width utilized frequency bands in **VDSL2** profiles. The profiles are differentiated by upper cutoff frequency, width of subchannel and a maximum total power of the transmitted signal.

Common parameters of VDSL2 connections profiles used in Europe.

Profile	Max. power in downstream [dBm]	Max. power in upstream [dBm]	Width of subchannel [kHz]	MBDC [Mbit/s]
8a	+17,5	+14,5	4,3125	50
8b	+20,5	+14,5	4,3125	50
8c	+11,5	+14,5	4,3125	50
8d	+14,5	+14,5	4,3125	50
12a	+14,5	+14,5	4,3125	68
12b	+14,5	+14,5	4,3125	68
17a	+14,5	+14,5	4,3125	100
30a	+14,5	+14,5	8,625	200

Frequency band cannot be used as a single unit. Subscriber wants through its single metallic lines to send and receive data. Therefore it is necessary to split the frequency band into at least two sub bands for two directions of transmission. To separate directions of traffic will use two basic methods. The first method is echo cancellation, the second method is the frequency division.

VDSL2 connection can only use the method of **FDD** with dedicated zones for both directions of transmission and the crossover between bands. This method reduces the effects of **NEXT** (*Near End Cross Talk*). Method **FDD** is therefore for this property preferred in **VDSL2** connection.

Parameter **MBDC** (*Minimum Bidirectional Net Data Rate*) represents the minimum value of the transmission rate, which is defined as the sum of transmission speeds in both directions. This value **MBDC** terminal must achieve in order to be classified for use in a given frequency profile. Speed **NDR** (*Net Data Rate*) is offered to the subscriber, and does not include requirements for the transmission of business information and header bits between **VDSL2** modems. Useful speed will be even lower than the value of **NDR** (part is used e.g. for header of Ethernet frames or **IP** packets).

2.9 Division of the frequency band

The situation is for **VDSL2** connections a little bit complicated. **VDSL2** connection must enable it to provide services that require both asymmetric and symmetric data transfers. For this reason, it is necessary to frequency sub bands further divided into smaller parts, and these parts rotate together sequentially so as to obtain the desired rate of data transfer in both directions, taking into account the increasing path loss. Rotation method and width of the individual frequency sub bands determined by the so-called as frequency plan. The sub bands for the downlink transmission direction (downstream) are identified and numbered as: D1, D2, D3, D4. The sub bands for uplink transmission (upstream) are marked and numbered as: US0, US1, US2, US3, US4.

There are two main frequency plans for **VDSL2** connection, which are based on plans for the **VDSL** connection. Plan known as the 998 is suitable for data transmissions with asymmetric transmission speeds. Plan, known as the 997 is suitable for services that require symmetrical data transfers.

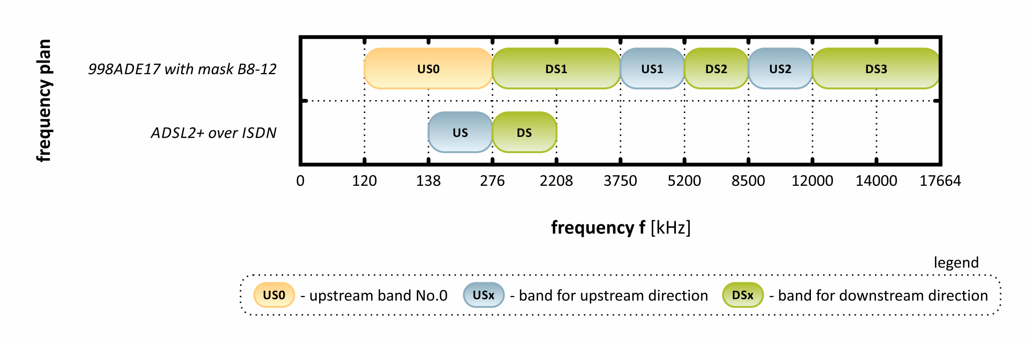


Figure illustrates how to use the frequency band at **ADSL2+** over **ISDN** connections and **VDSL2** operating with frequency plan 998ADE17.

2.10 Frequency plans for symmetrical data transfers

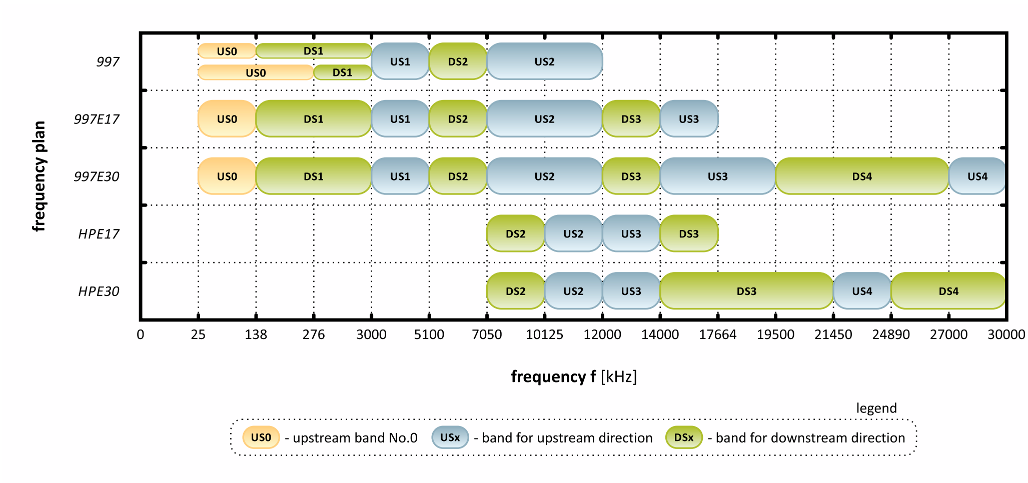
Usage of symmetrical data transfers is especially developed for small and medium-sized companies whose employees need data from the Internet not only download but also quickly upload. An example of service with symmetric transmission speeds may be more popular video, which was organized instead of conventional workshops.

It was noted in the previous chapter that it determined for symmetrical data transfer the fundamental frequency plan 997. This plan is further divided into next parts:

- 997 - fundamental frequency plan with the usual alternating bands for the downstream and upstream connections taken from **VDSL**,
- 997E - frequency plan with the usual alternating bands for the downstream and upstream extended to 17 MHz to 30 MHz, respectively,
- HPE - special frequency plan for the working connections between 7,05 MHz and 30 MHz (sections 17a, 30a).

Example of 997E frequency plan parameters for each profile **VDSL2** connections in Europe.

VDSL2 profiles	**The highest utilized subchannel**	**Upper limit frequency for downstream [MHz]**	**Upper limit frequency for upstream [MHz]**
8a	2047	7,05	8,832
8b	2047	7,05	8,832
8c	1182	7,05	5,1
8d	2047	7,05	8,832
12a	2782	7,06	12
12b	2782	7,05	12
17a	4095	14	17,664
30a	3478	27	30



Substitution each band in frequency plans for symmetrical data transfers.

2.11 Frequency plans for asymmetrical data transfers

Data transmission with asymmetric transfer rates are anticipated rather to domestic subscribers, where the transfer rate is in the downstream direction substantially higher than the transmission speed in the opposite direction.

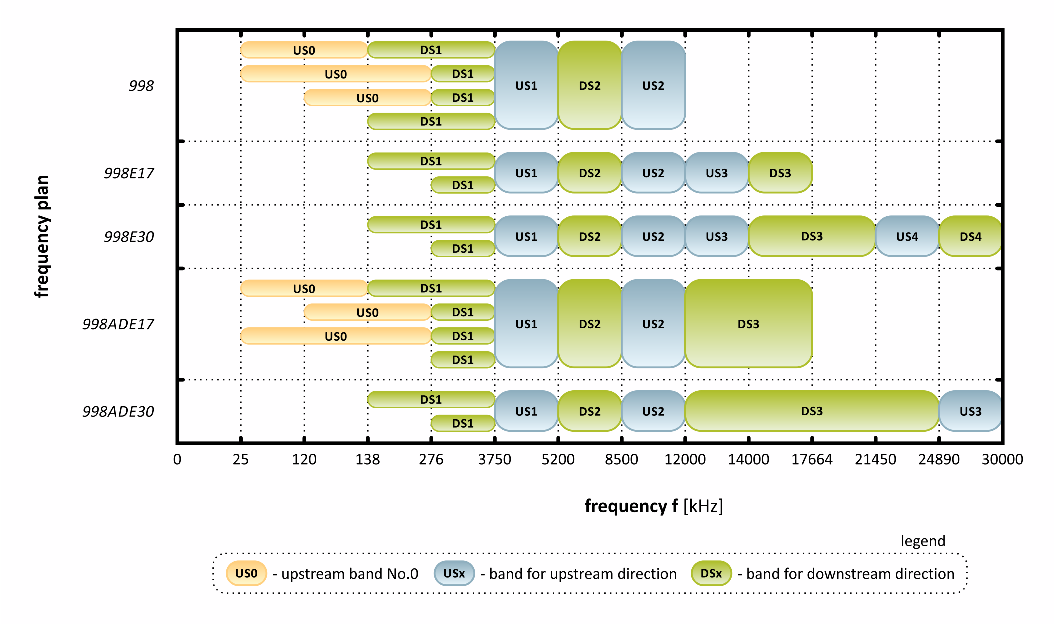
However, with regard to the number of sub bands for the upstream direction, should **VDSL2** connection in asymmetric transfer mode to achieve higher transmission rate than that of older **ADSL** connection.

Basic frequency plan 998 is further divided into:

- 998 - fundamental frequency plan with the usual alternating bands for the downstream and upstream taken from the first generation **VDSL** connections,
- 998E - frequency plan with the usual alternating bands for the downstream and upstream extended to 17 MHz, respectively up to 30 MHz,
- 998ADE - frequency plan designed for data transfer with significantly asymmetric speeds.

Example of 998ADE frequency plan parameters for each profile VDSL2 connections in Europe.

VDSL2 profile	The highest utilized subchannel	Upper limit frequency for downstream [MHz]	Upper limit frequency for upstream [MHz]
8a	1971	8,5	5,2
8b	1971	8,5	5,2
8c	1971	8,5	5,2
8d	1971	8,5	5,2
12a	1971	8,5	12
12b	1971	8,5	12
17a	4095	17,664	12
30a	2479	24890	30



Substitution each band in frequency plans for asymmetrical data transfers.

2.12 Masks of the power spectral density used in 997 plans

So far we have met with predefined profiles **VDSL2** connections have calendar as the frequency plans. Frequency plans determine which frequencies can be used for downstream or upstream. The maximum power level of the transmitted signal is nevertheless necessary determine to complete the definition of transmission parameters. Definition of performance level is going through a mask of the **PSD** (*Power Spectral Density*). The mask represents the peak power of the transmitted signal at a particular frequency.

PSD masks correspond with a specific frequency plan. The basic parameters are listed in the table below. Beyond the level of the transmitted signal, the individual masks also differentiate, for example, the use or non-use upstream bandwidth US0. The figure shows the progress masks 997E17-M2x-A. Parameters of the other masks for Europe are set out in the relevant Annex in the recommendation ITU-T G.993.2.

The basic parameters of the PSD mask for frequency plans 997.

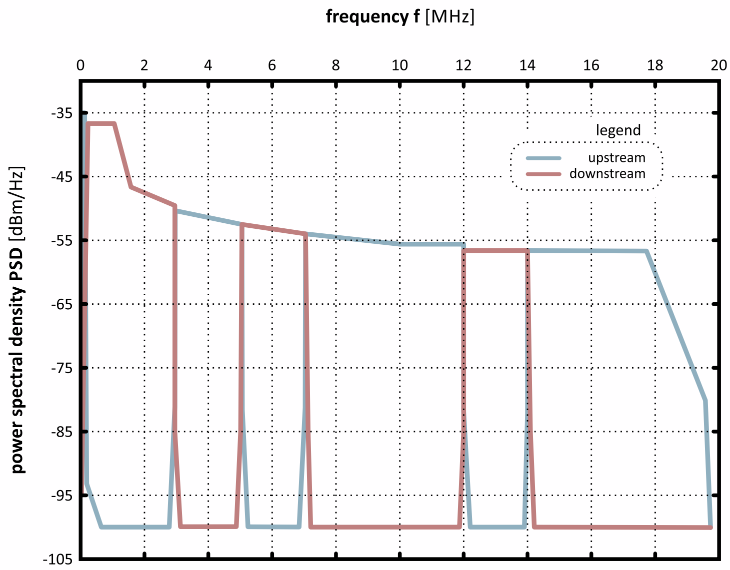
Shortcut	Label	Utilization of band US0	Upper limit frequency for upstream or downstream [kHz]
B7-1	997-M1c-A-7	A	7050
B7-3	997-M1x-M	M	12000
B7-7	HPE17-M1-NUS0	N/A	17664
B7-8	HPE30-M1-MUS0	N/A	30000
B7-9	997E17-M2x-A	A	17664
B7-10	997E30-M2x-MUS0	N/A	30000

The following conditions are valid for the upstream band US0 for each of masks:

A - corresponds to Annex A of ITU-T G.992.5,

M - corresponds to Annex M in the ITU-T G.993.2 or ITU-T G.992.5,

N/A - band US0 is not used for data transmission.



PSD mask 997E17-M2x-A with marked directions of transmission.

2.13 Masks of the power spectral density used in 998 plans

Total of 17 masks are defined in plans 998 in recommendation for **VDSL2** connection. Therefore, we show only the parameters for the two **PSD** masks that are used in the access network of the largest telecommunications operator in the Czech Republic.

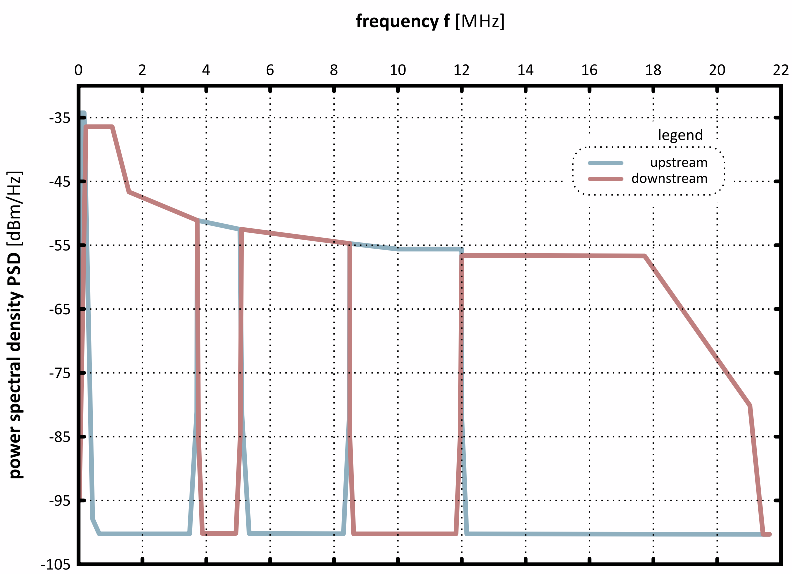
The basic parameters of the PSD mask that is used in access networks in Czech Republic.

Shortcut	Label	Utilization of band US0	Upper limit frequency for upstream or downstream [kHz]
B8-6	997-M2x-B	B	12000
B8-12	998ADE17-M2x-B	B	17664

The following conditions are valid for the upstream band US0 for each of masks:

B - corresponds to Annex B in ITU-T G.992.5.

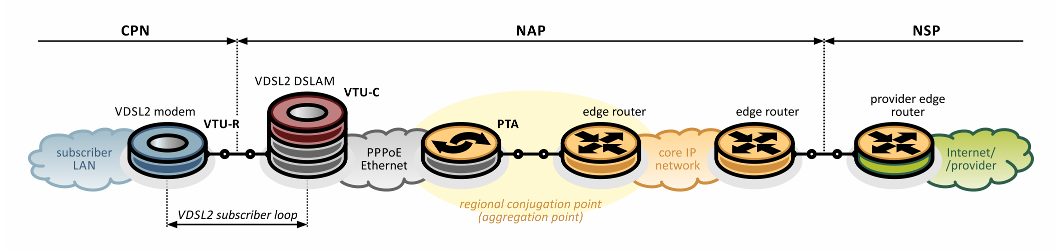
Both masks **PSD** used for the transmission of user data an upstream zone labeled US0. The choice of these masks provides suitable properties in spectral compatibility with already installed **ADSL**/ **ADSL2+** systems. Namely connections use the same frequency bands for the same direction of transmission, thereby eliminating crosstalk type **NEXT**.



PSD mask 998ADE17-M2x-B with marked directions of transmission.

2.14 Transmission chain of VDSL2 connections

Complete network architecture for high-speed data transmission and Internet access via xDSL is shown in next figure.



Transmission chain of VDSL2 connections.

Network architecture can be in general divided into next three parts:

- **CPN** (*Customer Premises Network*),
- **NAP** (*Network Access Provider*),
- **NSP** (*Network Service Provider*).

A distinctive feature of the concept is referred to the division between the **ISP** and service providers. Both roles can perform a single entity, but in connection with a variety of services and competitive environment in telecommunications is useful to separate the roles.

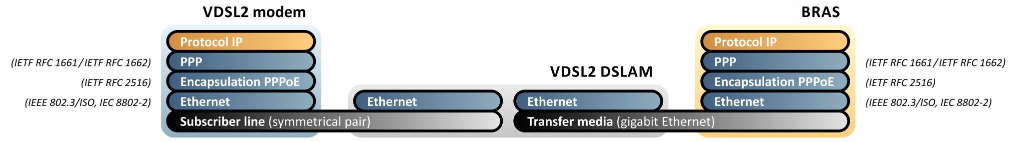
In the concept of subscriber network can include everything follows the terminating point of the network access provider (usually a telecommunications outlet), i.e. the terminal equipment, terminals, local data networks and **LAN**.

Provider **NAP** operates a technology for the physical transmission of signals from subscribers to the telecommunications nodes. In the case of **VDSL2** connections **NAP** is composed of copper symmetrical pairs (metallic conductions) that result from **CPN** and terminating in access multiplexers **DSLAM**. Multiplexers **ISP** connects to its own core network, of which there is a connection to the service provider.

Sources of data that is transmitted through the **NAP**, located in the network service provider **NSP**. For example, it may be just one company, typically a company operating an archive of TV programs, or may be formed by **NSP** de facto global network Internet.

2.15 Protocol structure of VDSL2 connections

Interconnection between the subscriber and the **ISP** service provider can be in general built on a different protocol architectures. Nowadays, we mainly use standard Ethernet, Point-to-Point Protocol and a family of protocols based on **TCP/IP**.



The protocol structure of VDSL2 connections for data transmission in PTM mode.

The transmission of **IP** packets is handled by using of **PPP** (*Point-to-Point Protocol*) at **VDSL2** connection in **PTM** mode, and these IP packets are encapsulated into Ethernet frames (*PPP over Ethernet*). In place of the termination of the **PPP** connection is performed authentication, authorization, accounting, allocation of IP addresses within the **PPP** connection, aggregation of data flows and other services. Those services meet the broadband access server **BRAS** (*Broadband Access Server*) of access provider in the aggregation point. **BRAS** from the server, the data is also transported the end user to the Internet or to individual service providers through a **VPN** (*Virtual Private Network*). This entire solution is referred to as variant **PTA** (*PPP Terminated Aggregation*).

3 High-speed subscriber lines according to G.fast standard

3.1 Standard G.fast – basic features

We can found in literature that the standard G.fast is called as the 4th generation **xDSL** system. The beginnings of the development of this standard are dated back to the beginning of February 2012. The standardization took place in 2014. The objectives of the new standard of **xDSL** are several:

- higher transfer rates in comparison with the existing type of **xDSL** connections - up to 500 Mbit/s to circa 100 m, respectively 150 Mbit/s to 250 m (it is also considering about transfer rates up to 1 Gbit/s)

- utilization of short lengths of subscriber lines, called ad **FTTdb** (*Fiber To The distribution point*) - the location of distribution points will be very close to subscribers (up to 250 meters) - equivalent to the concept of **FTTB** (*Fiber To The Building*)

- inverse power

- the possibility of self-installation service with parameters of optical connections and simplicity of **xDSL** connections

All the above mentioned objectives are closely related into two key areas. The first area is the question how to increase throughput, the second is an area of increasing reliability. Throughput of connections can be increased in two ways:

- extension of the frequency band - this option was used in the previous generation of **xDSL** with the demand for spectral compatibility with **VDSL2** systems
    - Mask of **PSD** – beginning at 138 kHz; 2,5 MHz; 18 MHz a 30 MHz and end at 106 MHz; 212 MHz a 300 MHz
    - Respect for additional frequency bands, such as **VHF** broadcast (usually called as "Western Standard" in Europe), **DAB** (*Digital Audio Broadcast*) - so called as III. TV band 174-240 MHz.

- cancellation of crosstalks - a process of elimination of crosstalk type **FEXT** (*Far End Cross Talk*) using the appropriate modulation type called as **VDMT** (*Vectored Discrete Multi Tone*)

Increasing the reliability of the entire system provides by the following two mechanisms:

- inverse multiplex

- phantom circuits

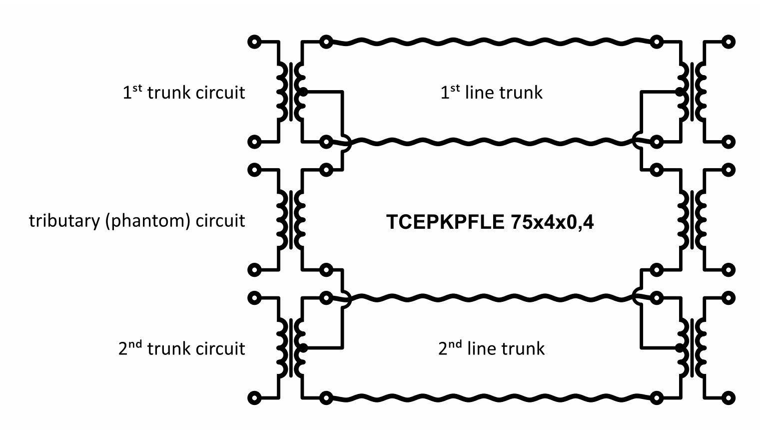
In contrast to **ADSL** and **VDSL**, which use **FDD**, the connections with the extreme bandwidth uses **TDD**. This allows for much more efficient and flexible allocation of bandwidth and eliminates the dilemma of allocating bands for each direction of transmission. Time synchronization is not a problem, because they must be dealt already with regard to the modulation **VDMT**.

Introduction of **TDD** also provides simple support for saving modes. In the context of **TDD** duplex mode timing are introduced mandatory divider ratios of 90/10 and 50/50, an optional divider ratios are then from 50/50 to 10/90.

Among the last-mentioned, but key features of a standard G.fast include the implementation of adaptive modulation **DMT** with required support **VDMT**.

3.2 Utilization of phantom circuits

Phantom circuits previously used for long-distance telephone lines to increase transmission capacity. The principle is to establish a signal to transformer centers of two lines and thus create additional circuit. The use of this principle is limited towards increasing frequency impossibility of precision balancing symmetrization transformer and increasing crosstalk between the majors and the phantom circuit. Mentioned phenomena can be eliminated by suppressing of crosstalk through modulation **VDMT** and achieve e.g. summary speeds up to nearly 500 Mbit/s in both directions at a length of cable 400 m.



Principle of phantom circuit

Transmission speeds for high-speed xDSL systems modeled on a cable with a length of 400 m

Model for length of cable 400 m	**Frequency plan VDSL2 up to 17 MHz**		**Frequency plan VDSL2 up to 30 MHz**	
	downstream [Mbit/s]	**upstream [Mbit/s]**	**downstream [Mbit/s]**	**upstream [Mbit/s]**
2 lines plus phantom	150	67	176	80
2 lines	166	92	226	118
2 lines plus phantom with crosstalks cancellation	382	243	493	449

Outside the phantom circuits can be realized even more so called as superphantom with 4 lines. So you can get a total of 7 circuits: 4 basic, 2 phantoms and among them one superphantom.

Besides the phantom lines has done experiments with transmission in unison mode, where the individual wire pairs are taken as separate transmission paths. The resulting strong crosstalk can be compensated by also using **VDMT** modulation. This solution, however, an advantage to prepare symmetrical conduction, i.e. a significant resistance against ambient interference. For reasons of considerable mutual interference between the wires and the environment, therefore this kind of practice did not catch on.

3.3 Power supply of optical node from the user modem

In classic analogue and **ISDN** basic implementing the power of the terminal equipment from the exchange (typically a power supply voltage of 60 V and a supply current of tens of mA). In connection with extreme speed as specified by the working title G.fast is expected to reverse the flow of power.

The node (mini **DSLAM**) will be power supplied from the local modem in the point that is called as “Distribution point”. The reason for this approach to solving the many years solving problems with power equipment placed in the access network between the **PBX** (*Private Branch eXchange*) of telecommunications operator and the subscriber.

Devices in the distribution point is connected to a provider network through optical fiber, so it is not possible to realize the remote power supply by signal line.

Solution of local power supply from a grid is usually problematic. The logical outcome is therefore the power supply from the subscriber side, where it is necessary to summarize the power output from multiple participants at once.

3.4 Vector Modulation – VDMT

DMT modulation is used by the **xDSL** for the most effective use of the potential of metallic symmetrical pairs and allows you to respond appropriately to the existence of narrowband interference in the frequency channel. For **xDSL** with DMT modulation, due to the nature of the transmission environment shared metallic cable, can further increase the transmission speeds achievable using so-called as vector modulation **VDMT** (*Vectored DMT*).

The dominant component of the interference, which limits the transmission speed of **xDSL** systems is crosstalk interference.

Crosstalk is signal transmission capacitive and inductive relationships between pairs. Thus a transmitted signal, for example, from the first pair to the other pair operates in the second pair of negative interference and decreases the **SNR** (*Signal-to-Noise Ratio*) and thus the resultant transmission rate. Given that prevent cross talk is not possible due to the structure of a copper cable and the properties of electromagnetic waves, it is necessary to eliminate the effects of crosstalk on the transmitted useful signal. Elimination of crosstalk ensure the improvement of the **SNR** and thus the higher the achievable transmission rate. According to the site crosstalk measurement, we distinguish between **NEXT** (*Near End Cross Talk*) and **FEXT** (*Far End Cross Talk*). **NEXT** crosstalk can be eliminated by using a frequency division transmission directions. Size of **FEXT** crosstalk is therefore crucial for **xDSL** connections.

Modulation principle of **VDMT** uses sophistication of mathematical apparatus describing the characteristics of symmetrical pairs of crosstalk and mutual ties between couples. It is possible to differentiate the direction of transmission for their elimination.

In the downstream direction **VDMT** exploits the fact that the device **DSLAM** is a common element for all xDSL connections operated in harness copper cable. Thus in the **DSLAM** we have a single point of information on DMT symbols to be sent in the next moment to stretch metallic lines (i.e. we vector values of DMT symbols - hence vectored modulation DMT). Given that in the **DSLAM** also known parameters of the various symmetrical pairs of crosstalk and the links between them (known is a process of establishing a connection), it is possible to modify the transmitted DMT symbols with respect to transmission media, which will be transmitted. On the receiving side modem end user will then have the symbols theoretically ideal course and parameters suitable for error-free detection. Problems synchronization transmission is also easily manageable since it is the central element of the **DSLAM**. Synchronization of transmission of DMT symbols is needed. Symbols are transmitted at each other through crosstalk bonds have a defined cause, as calculated during their preparation.

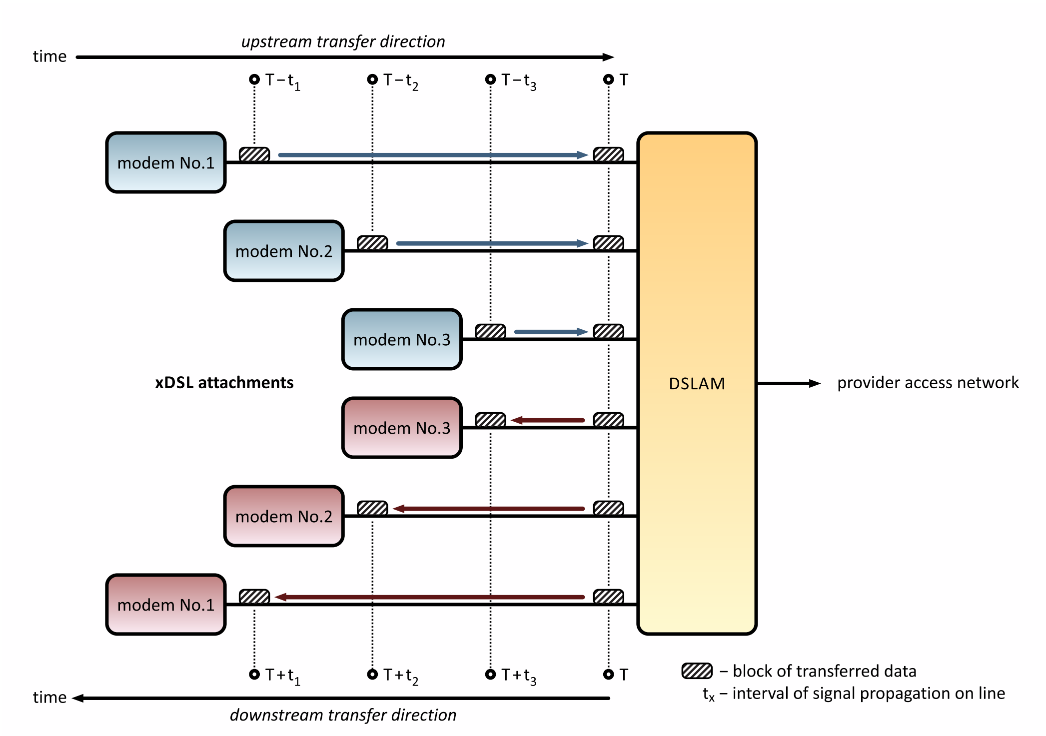
In the upstream direction it is not possible to adjust the transmitted symbol in the terminal equipment of a subscriber. That would place increased demands on equipment and computational efficiency of terminal equipment. In addition, the terminal equipment can never have information about the symbols that are broadcast by other connections in metallic cable. Therefore, it is necessary to modify only the received signal again in the **DSLAM** (the central element) using a special block crosstalk canceller. An important question is also necessary to synchronize the transmissions from the subscribers towards the end **DSLAM** with respect to different length loops.

VDMT is an extension of DMT modulation in a multi-user environment, that solves the problem of **MIMO** type and type eliminates crosstalk **FEXT**. Crosstalk **NEXT** crosstalk is eliminated by frequency division transmission directions.

With regard to co-location of modems in **DSLAM** it can provide synchronous broadcast DMT symbols in the downstream direction. Ensure synchronous transmission of symbols from the users to the access multiplexer **DSLAM** is due to the different lengths of the individual connections more complicated, but can use a method such as FDD Zipper.

Synchronization in the upstream direction is parallel to the procedures for medium access control in a shared environment point - a lot of points, such as passive optical networks and radio networks **LDMS** (*Local Multipoint Distribution System*). Broadcasting in subscriber modems must be timed with respect to different times of propagation of signals along different lines from remote participants.

FDD Zipper method uses **CS** (*Cyclic Suffix*). This is unlike the **CP** (*Cyclic prefix*) is inserted per DMT symbol. The length of **CS** must be equal to or greater than the maximum difference in propagation delay of the signal channels. FDD Zipper method also eliminates the residual crosstalk **NEXT**. The disadvantage of this method is a reduction of transmission rate.



The principle of synchronization of symbols at xDSL connection in the upstream direction.

3.5 Advantages and disadvantages of VDMT

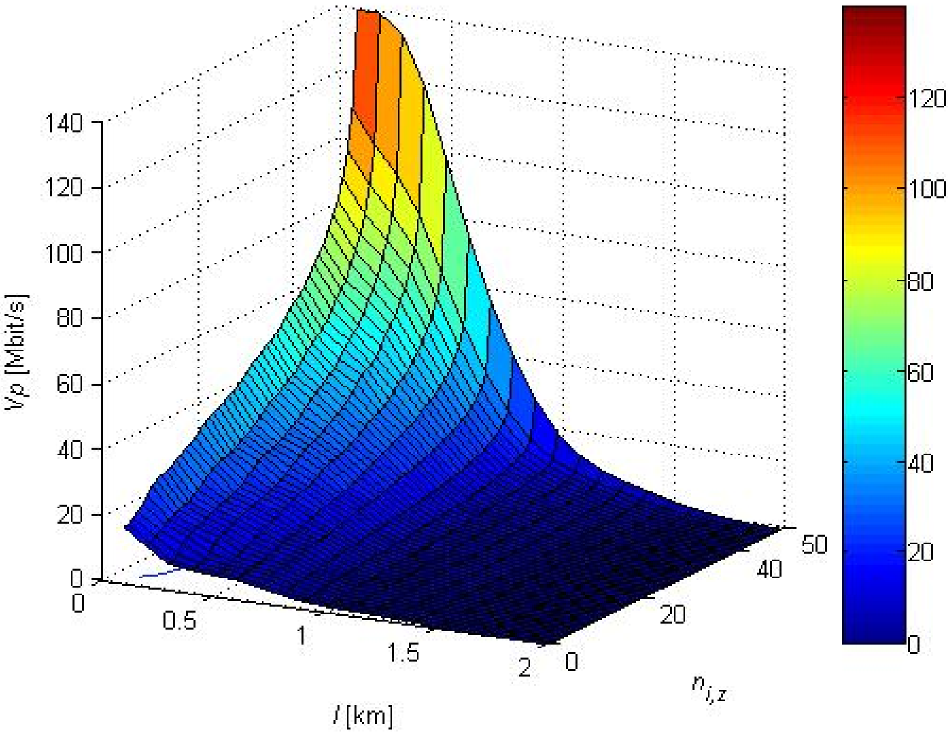
The main advantage of the modulation principle **VDMT** has already been mentioned.

The purpose of the modulation principle **VDMT** is to eliminate crosstalk interference and thus to achieve higher transmission speeds reachable by **xDSL** connections.

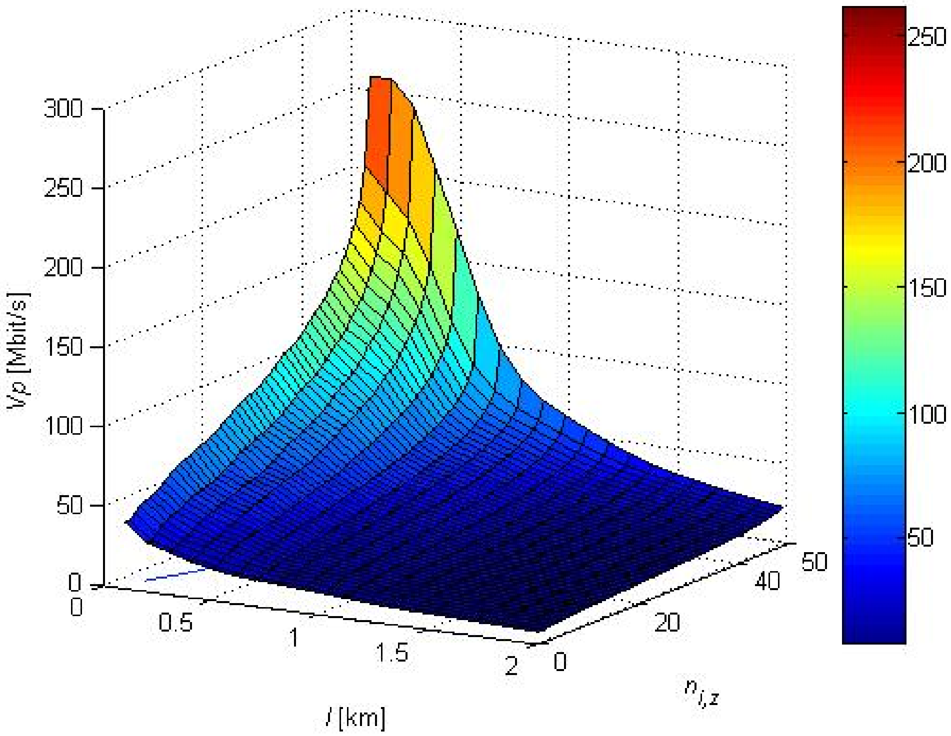
The process is called as crosstalk coordination. We talk about the coordination of individual broadcast connections in a bundle copper cable in connection woth modulation **VDMT**.

Since it is possible the principles and parameters of the analytical models describe the connections may be relatively simple to calculate and benefits VDMT modulation. Depending on the number of connections increases coordinated achievable transmission rate monitored connection. The following simulation was performed after a **VDSL2** connection with the frequency plan B8-13, which has a bandwidth up to 30 MHz. The frequency plan allows routinely achieve transmission speeds of 100 Mbit/s. Graphical interpretations of increasing transmission speeds for the upstream and downstream direction is shown in the following figures.

For the purposes of the simulation was considered metallic cable bundle with 50 symmetrical pairs, with a diameter of 0.4 mm wire (cable TCEPKPFLE 50×4×0,4 mm). The benefits of coordination are modeled as depending on the length of the subscriber line. It ranged from 0.1 km to 2 km with step 0.1 km. Number of coordinated connections gradually increased from 0 to 49. Taking connection with the fiftieth monitor the performance of transmission (reachable bit rate). Volume copper cable connections **VDSL2** is therefore fully occupied.



The benefits of coordination for the upstream direction and VDSL2 connection B8-13.



The benefits of coordination for the downstream direction and VDSL2 connection B8-13.

When analyzing the benefits of **VDMT** be used for this test case indicate that the length of the local loop 0.5 kilometers is possible without any coordination (full cast all couples xDSL connections) will reach in the direction downstream transmission rate of 16.676 Mbit/s. If we coordinate our broadcast connection and a further connection, which causes the most crosstalk our reference, we are able to achieve data rates in the downstream direction of 19.84 Mbit/s. If we coordinate broadcasts from five surrounding connections, reach 27.960 Mbit/s. In the coordination of twenty seven speeds reach 50.868 Mbit/s. If we carry out the full coordination of connections reaches our tracked in the direction downstream connection speed of 170.720 Mbit/s. **VDMT** benefits are so obvious.

Modulation VDMT has also the significant disadvantages too.

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Disadvantage of modulation VDMT is the high computational complexity in coordinating of the broadcast.

VDMT principle is to modify each currently transmitted DMT symbol on each symmetric pair with respect to the current parameters of the transmission environment. It is therefore obvious that for full coordination of all connections with DMT modulation, it is necessary to know the function describing crosstalk links between all pairs of lines, the transmission function of each line and the currently transmitted DMT symbols all coordinated connections. For copper cables with several hundred pairs of symmetric implementation will be fully operational coordination very difficult calculations associated with the adjustment of DMT symbols and calculations related to the acquisition parameters transmission environment. It can be calculated that, for example, only 50 connections of **VDSL2** with the 4096 subchannels and modulation rate 4 kBaud will have to make every second in the respective **DSLAM** only when editing the transmitted DMT symbols 40,960E9 mathematical operations. Additional computing power then you need when establishing a connection, control and direction of current connections, etc.

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Modulation VDMT has benefits only in a situation where the propagation medium is used by all systems with DMT modulation. This requirement follows from the principle of **VDMT**.